Toward a Space-based Gravitational Wave Observatory

Robin Stebbins, GSFC

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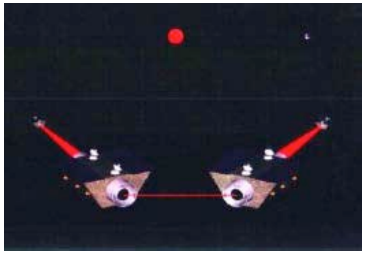
Outline

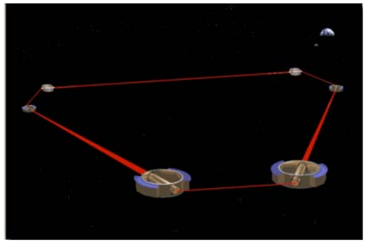
- History
- Science
- Concepts
- Current activities
  - LISA Pathfinder
  - ESA's L3
  - Technology
  - Near term activities

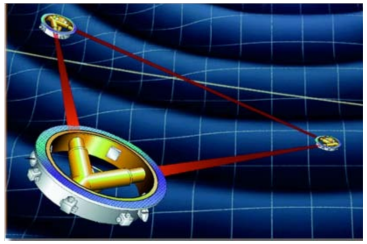
A BRIEF HISTORY OF GRAVITATIONAL WAVES IN SPACE

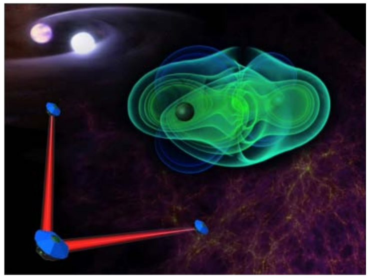
A Brief History of LISA, NASA & ESA

- 1974 - A dinner conversation and NASA report
- 1985 – LAGOS Concept (Faller, Bender, Hall, Hils and Vincent)
- 1993 – LISAG - ESA M3 study: six S/C LISA & Sagittarius
- 1997 - JPL Team-X Study: 3 S/C LISA
- 2000 – Decadal recommendation for new start
- 2001-2015 - LISA Pathfinder and ST-7 DRS
- 2001 – NASA/ESA project began
- 2004 – Phase A started
- 2007 – NRC BEPAC Review
- 2010 – Decadal recommendation for new start
- 2011 – NASA/ESA project ended
- 2013 – ESA selects GW mission for L3









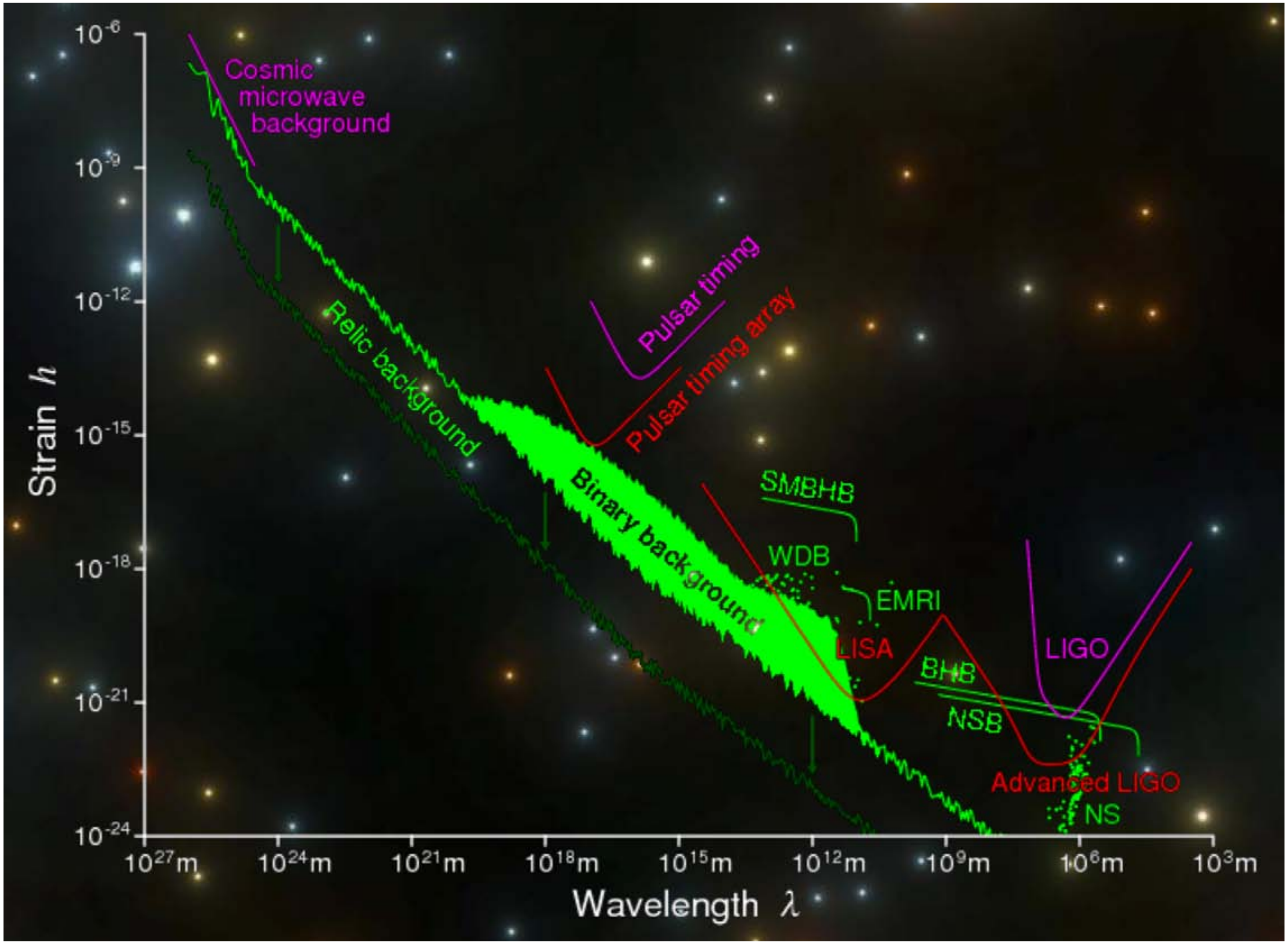
The history of major reviews

The LISA concept has always gotten high rankings in NRC reviews:

- AANM (2000) decadal: highest priority medium new start
- Quarks to Cosmos: proceed to develop
- Beyond Einstein Program: highest priority science
- NWNH (2010) decadal: second priority large mission after WFIRST

GRAVITATIONAL WAVE SCIENCE

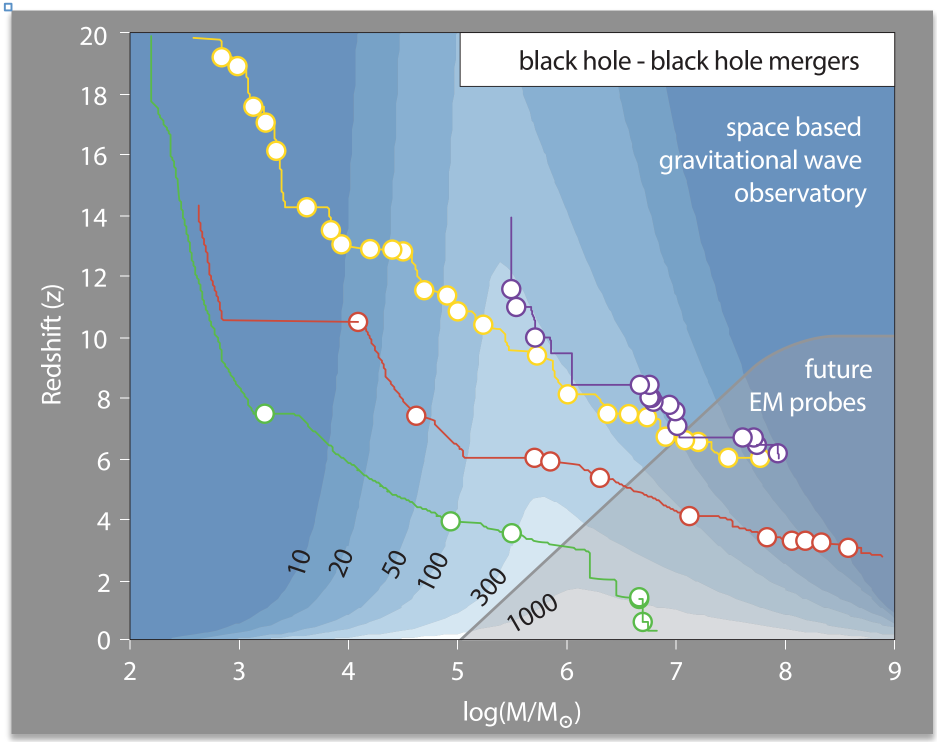
Gravitational Wave Spectrum



Credit: Teviet Creighton

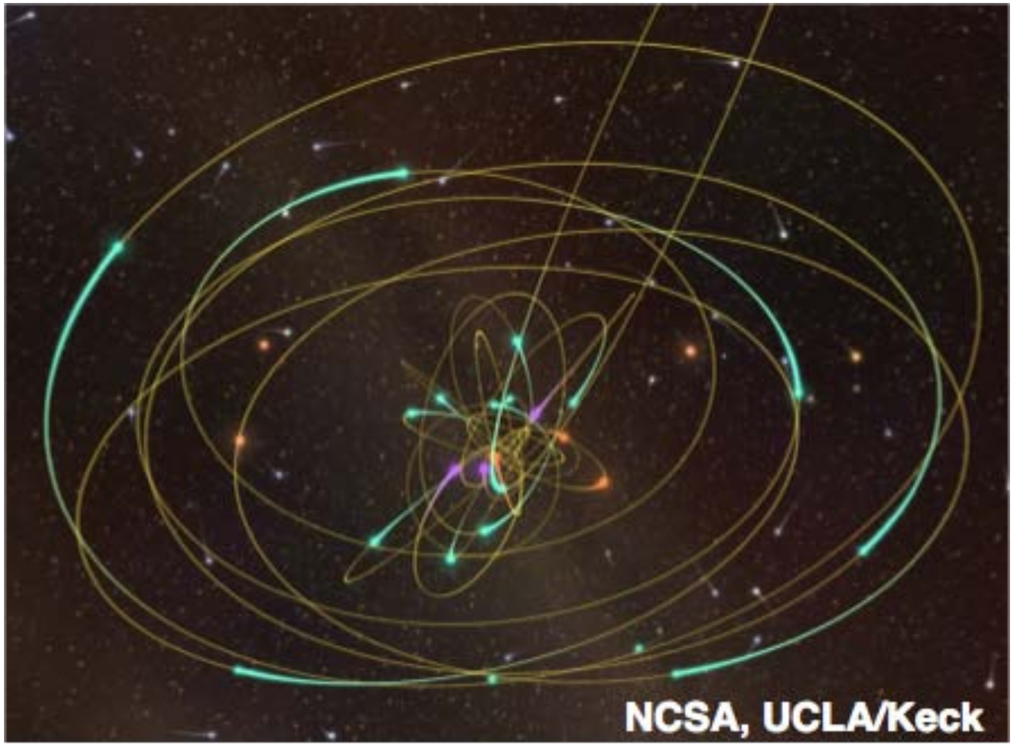
Origin and growth of massive black holes

- Observe: MBHs from 10^3 to 10^7 $M_\odot$, z<20 radiate in LISA band as some point; 10's of events per year
- Measure: masses, spin vectors, luminosity distance, sky position, etc.
- Learn about:
  - MBH seed population
  - Growth mechanisms vs redshift
  - Merger history before earliest quasars



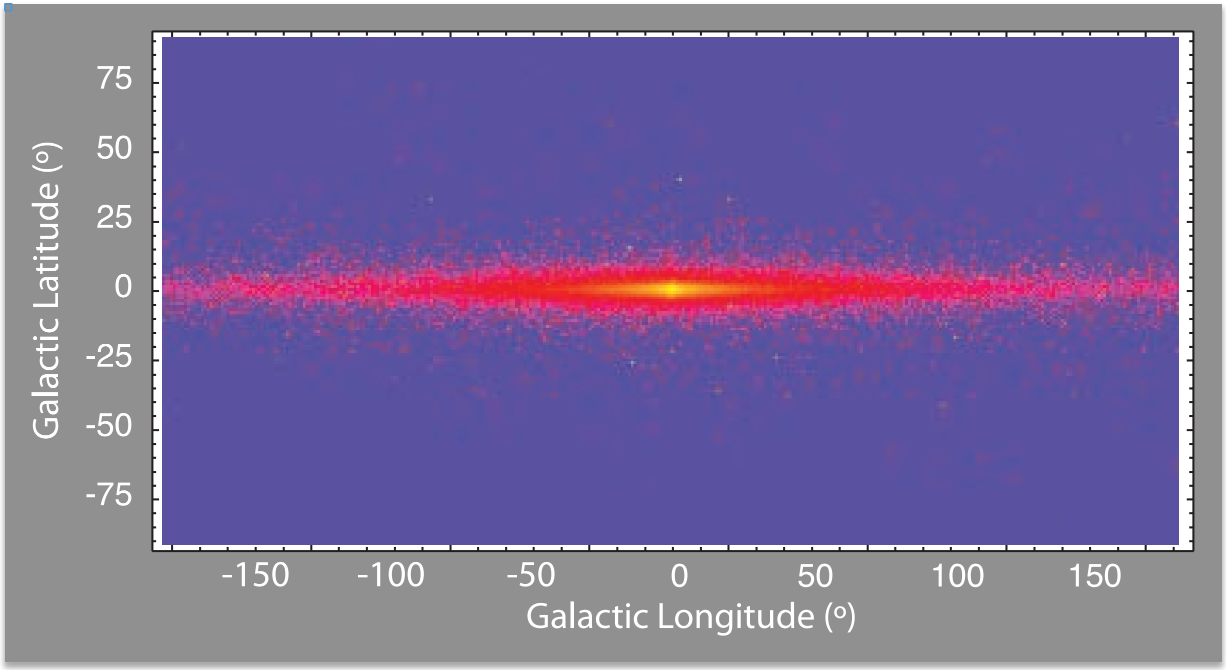
Stellar populations and dynamics in galactic nuclei

- Observe: stellar mass compact objects spiraling into MBHs (EMRIs), $z \lesssim 1$; 10's-100's of events per year
- Measure: masses, spin vectors, luminosity distance, sky position, etc.
- Learn about:
  - Stellar populations in galactic nuclei
  - Intermediate mass BHs
  - Detailed geodesy of MBH spacetime



Compact stellar-mass binaries and structure of the galaxy

- Observe: millions of close compact binaries in the galaxy, tens of thousands individually resolvable, some electromagnetically observed.
- Measure: chirp mass or individual masses if evolving, orbital parameters, period evolution if interacting
- Learn about:
  - Demographics
  - Shape of the galaxy
  - Close binary evolution
  - Type 1a progenitors



Fundamental Physics and Cosmology

- Observe: waveform evolution, merger dynamics, higher harmonics in ring-down, spacetime mapping
- Measure: precise waveform phase and amplitude, luminosity distances over a wide range of redshifts, waveforms with electromagnetic counterparts
- Learn about:
  - Test GR in dynamical, strong-field gravity, constrain alternative theories
  - Fundamental properties of GWs: speed of propagation, polarization states
  - Fundamental properties of black holes: no-hair, Kerr
  - Hubble expansion out to large redshifts
  - Cosmic expansion history, geometry and dark energy
  - Exotic and unforeseen sources

Recent Advances in GW Astrophysics

- Improvements in MBHB parameter estimation
  - Added merger and ring-down phases to waveforms
  - Added higher harmonics to waveforms
  - Improved understanding of sky localization, especially from merger phase
  - Orbital eccentricity explored
  - Improved understanding of the interaction between SMBHs and their host galaxies, including effects of eccentricity and spin alignments
  - Kicks explored
  - Improved cosmological modeling of structure formation
  - Better understanding of final parsec problem and its resolution
- Emerging methods for quantifying GR tests
- Improved galaxy models
- Science performance calculations
  - ~50 mission concept variants analyzed

2010s – The GW Decade

Advanced LIGO/Virgo/KAGRA begin operations

- O1 observing run began September 18th for 3 months
- Reach 70 Mpc for NS-NS mergers, 3 times previous LIGO distance (27 times volume)
- Progressive sensitivity improvement in next few years
- First GW observations expected by ~2019

Pulsar Timing Arrays (PTAs)

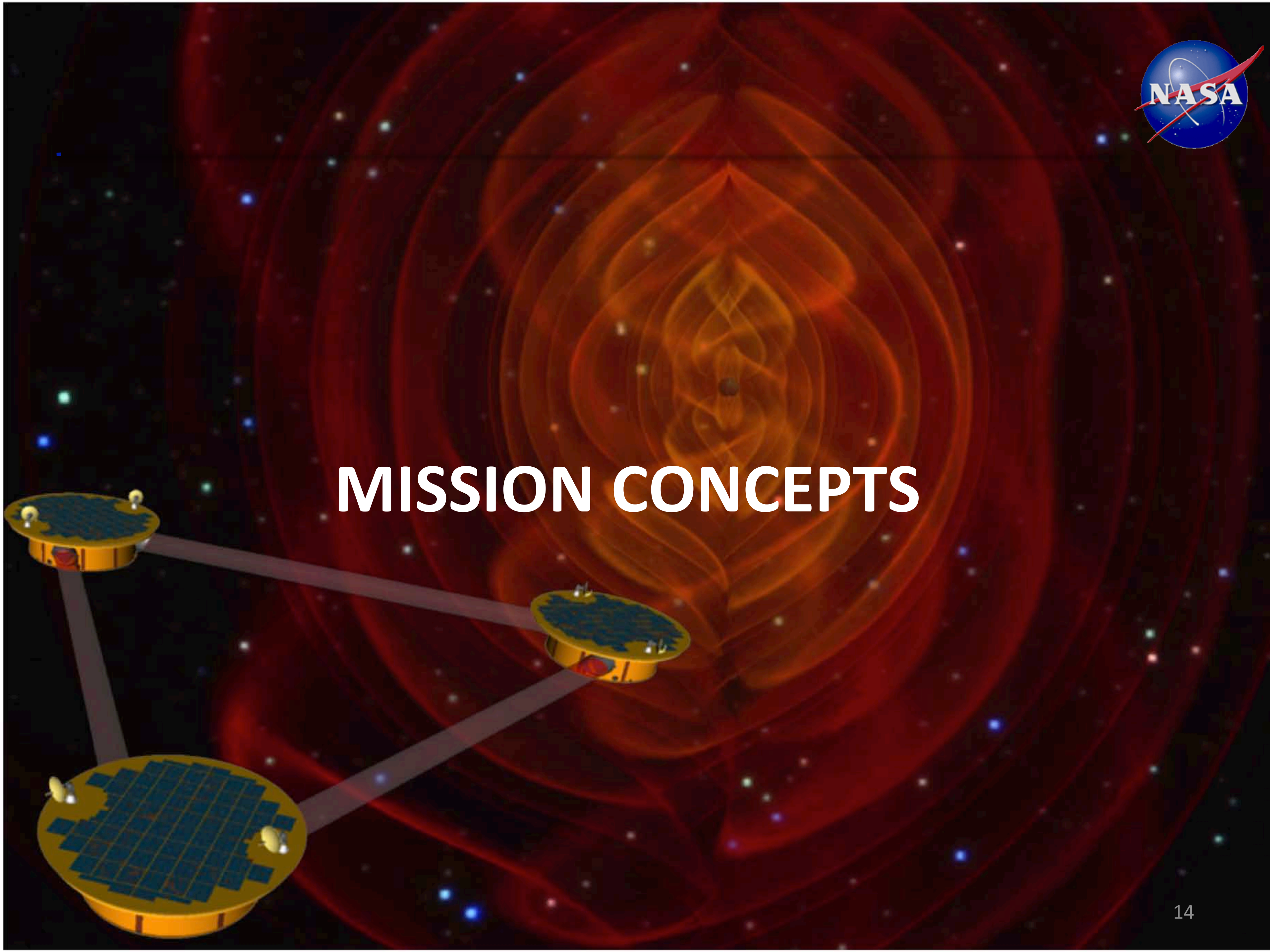
- PTA efforts have published upper-limits on stochastic GW backgrounds from SMBH binary mergers (NANOGrav, EPTA, PPTA)
- A key astrophysical uncertainty is in the strength of SMBH binary interactions with their environments
- Recent (2015) results from Parkes (PPTA) are in conflict with models that assume modest rates of evolution passing through the nHz band.
- Models less sensitive to environmental effects at higher frequencies

LISA Pathfinder launch and operation

Caltech/MIT/LIGO Lab

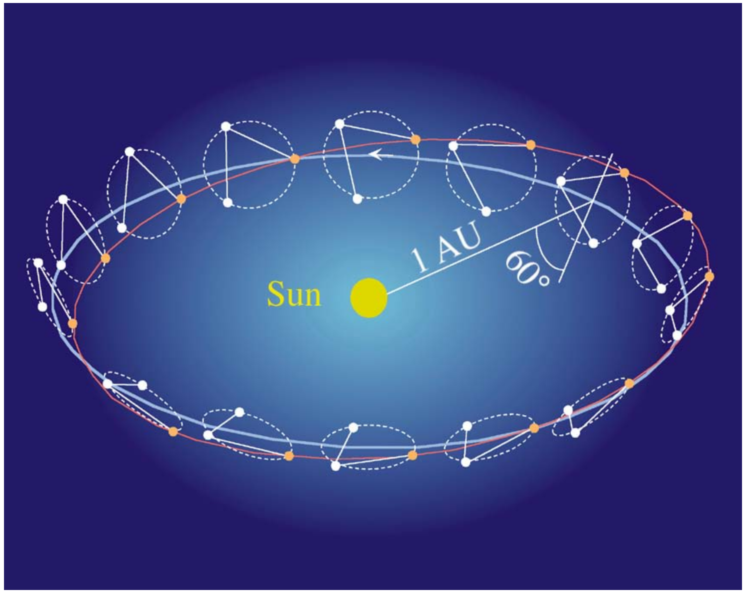
Caption: CSIRO's Parkes radio telescope. Credit: David McClenaghan, CSIRO

MISSION CONCEPTS

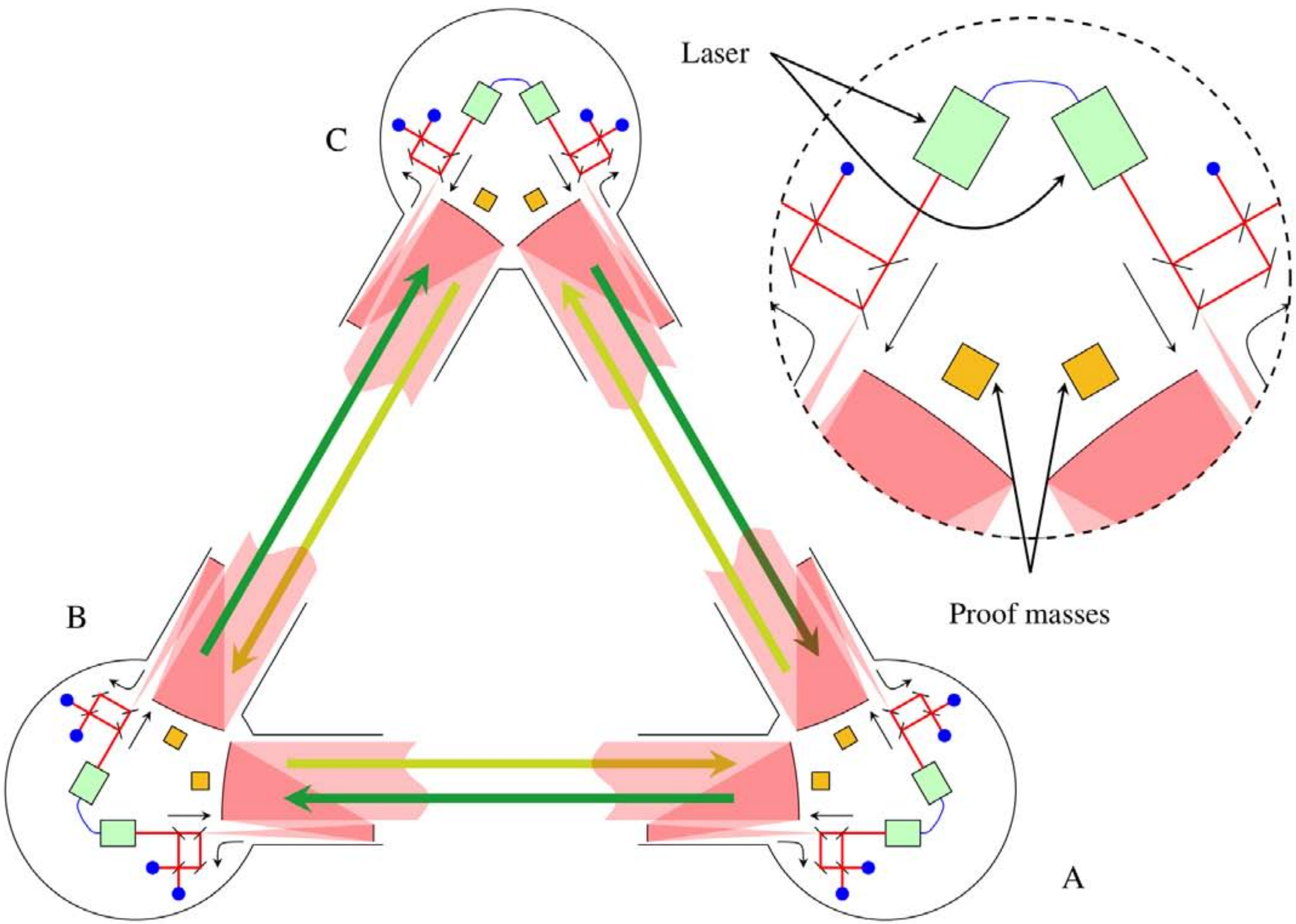


LISA Concept

- Measure changes in 'time-of-flight' between test masses
  - Continuous laser ranging between free-falling test masses
  - Interferometric readout (μcycles/√Hz over gigameters with 1μ light)
  - Performance characterized by noise in measurement of displacement
- Reduce disturbances on those test masses
  - Benign environment
  - Enclosed test masses
  - Control disturbances from spacecraft
  - Limit relative motion of spacecraft with "drag-free" control
  - Performance characterized by residual acceleration noise



LISA Concept



Mission Concept Study

In 2012 NASA studied the impact of design trade-offs on science, cost and risk, looking for a mission concept $\lesssim$\$1B.

The findings can be summarized as follows:

- No concepts were found near or below \$1B.
- No technology was found that dramatically reduces cost.
- The LISA architecture can be scaled down somewhat, and still do compelling science.
- Science performance decreases far more rapidly than cost. At some point, risk increases to an unacceptable level for missions of this scale.

Mission Concept Comparison

Parameter	NGO	SGO Mid	LISA
Measurement arm length	1 x 10^6 km	1 x 10^6 km	5 x 10^6 km
Number & type of spacecraft	1 corner (2 optical assemblies, 2 end (single optical assembly	3 corner (2 optical assemblies)	3 corner (2 optical assemblies)
Number of measurement arms, one-way links	2 arms, 4 links	3 arms, 6 links	3 arms, 6 links
Constellation	Vee	Triangle	Triangle
Gravitational-wave polarization measurement	Single instantaneous polarization, second polarization by orbital evolution	Two simultaneous polarizations continuously	Two simultaneous polarizations continuously
Orbit	Heliocentric, earth-trailing, drifting-away 9°- 21°	Heliocentric, earth-trailing, drifting-away 9°- 21°	22° heliocentric, earth-trailing
Trajectory	Launch to Geosynchronous Transfer Orbit, transfer to escape, 14 months	Direct injection to escape, 18 months	Direct injection to escape, 14 months
Duration of science observations	2 years	2 years	5 years
Launch vehicle	Two Soyuz-Fregat	Single Medium EELV (e.g., Falcon 9 Block 3)	Single Medium EELV (e.g., Atlas V 551)
Optical bench	Low-CTE material, hydroxy-catalysis construction	Low-CTE material, hydroxy-catalysis construction	Low-CTE material, hydroxy-catalysis construction
Laser	2 W, 1064 nm, frequency and power stabilized	1 W, 1064 nm, frequency and power stabilized	2 W, 1064 nm, frequency and power stabilized
Telescope	20 cm diameter, off-axis	25 cm diameter, on-axis	40 cm diameter, on-axis
Gravitational Reference Sensor	46 mm cube Au:Pt, electrostatically controlled, optical readout	46 mm cube Au:Pt, electrostatically controlled, optical readout	46 mm cube Au:Pt, electrostatically controlled, optical readout

Science Comparison

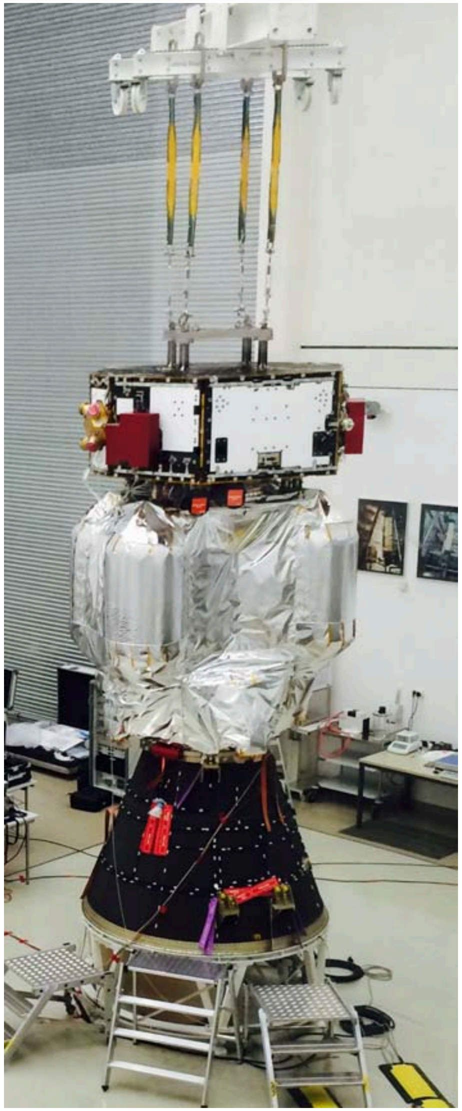
	NGO	SGO Mid	LISA
MBH Totals	40-47	41-52	108-220
Detected z > 10	1-3	1-4	3-57
Both mass errors < 1%	13-30	18-42	67-171
One spin error < 1%	3-10	11-27	49-130
Both spin errors < 1%	<1	<1	1-17
Distance error < 3%	3-5	12-22	81-108
Sky location < 1 deg^2	1-3	14-21	71-112
Sky location < 0.1 deg^2	<1	4-8	22-51
EMRIs	12	35	800
Resolved CWDBs	3,889	7,000	40,000
Interacting	50	100	1,300
Detached	5,000	8,000	40,000
Sky location < 1 deg^2	1,053	2,000	13,000
Sky location < 1 deg^2, distance error < 10%	533	800	8,000
Stochastic Background	0	0.2	1

Special acknowledgement to Ryan Lang (Univ. of Florida) and Neil Cornish (Montana State Univ.)

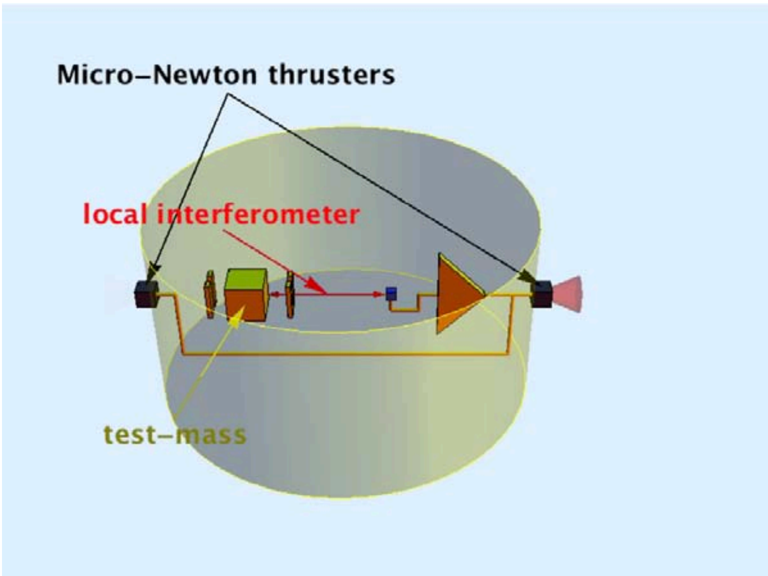

LISA PATHFINDER

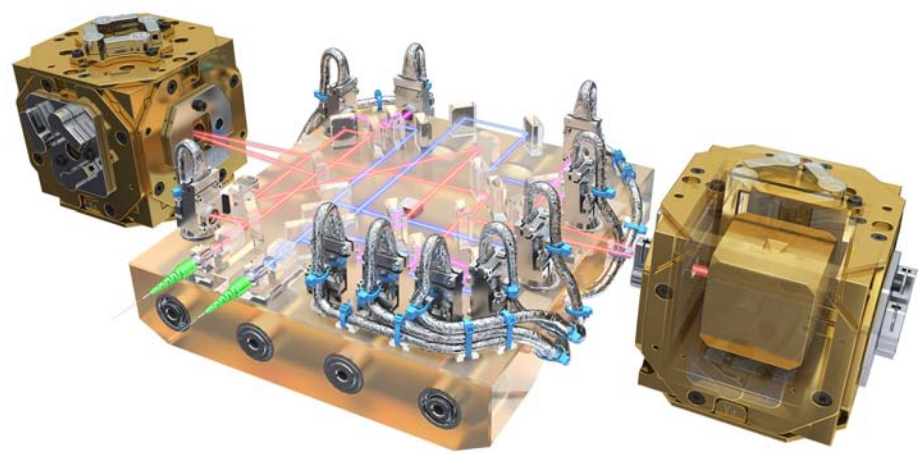
LISA Pathfinder

- Mission to demonstrate technology for a LISA-like gravitational wave observatory
- European payload has Gravitational Reference Sensors, interferometer and “drag-free” control system.
- NASA participation in European payload operations and data analysis
- NASA payload, called ST7 Disturbance Reduction System, has micronewton thrusters and “drag-free” control system.
- Launch in December 2015.



LPF – The Basic Idea





- Drag-free control system
  - One test mass as a sensor
  - Microthruster as a forcer.
  - Controller
- Second test mass as a “witness.”
- Measure the relative motions of the two test masses with picometer interferometer

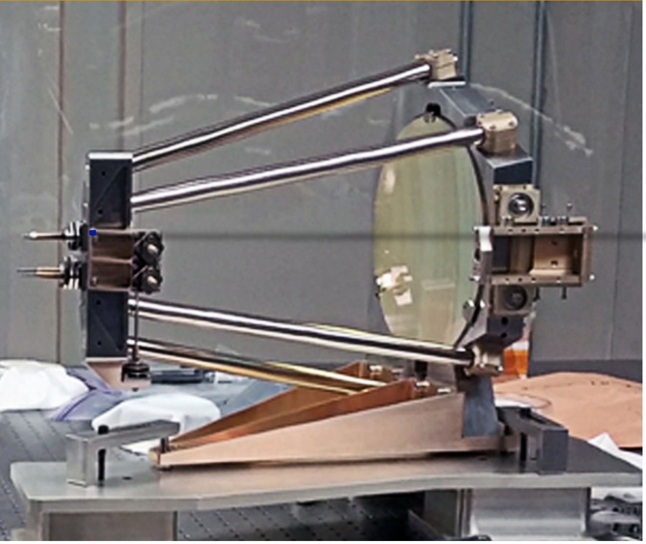
LPF Objectives

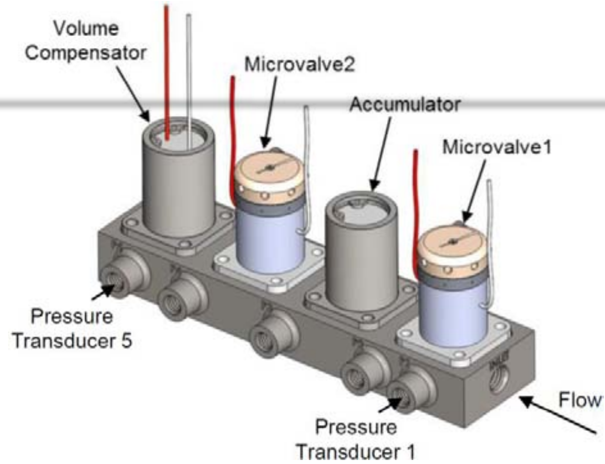
- Drag-free flight demonstration
  - Residual acceleration on the test mass $<3\times10^{-14}$ m/sec^2/√Hz at 1 mHz
  - Multi-degree-of-freedom control system
- Microthruster demonstration
  - Thrust noise
  - Controllability
- Error budget validation
  - Programmable environment disturbances (magnetic, thermal, charging)
  - Measure the transfer function
  - Extrapolate to LISA

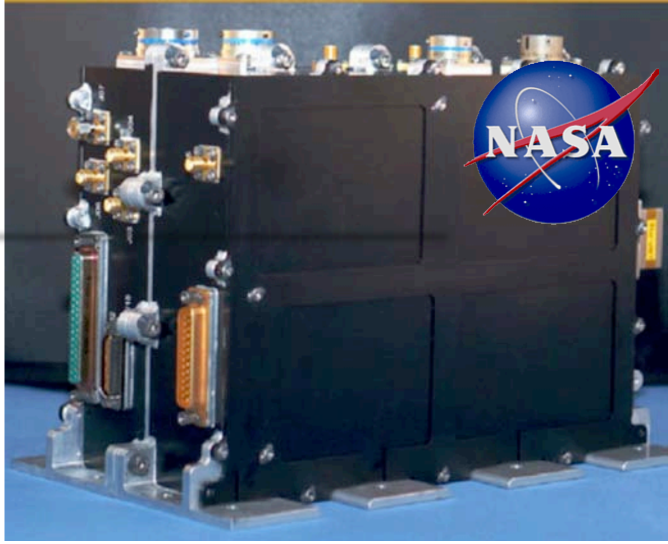
LPF – Status

- Design, fabrication, assembly and test of the flight system completed September 1st
- Final ground testing met or exceeded all requirements.
- October 8: Flown to Kourou, start of the launch campaign
- December 1, 11:15 pm EST: scheduled launch on Vega 6 (38 days, 8 hours, 21 minutes @ 3:54 pm EDT)
- L+74 d: LTP operations start
- L+186 d: ST7 operations start
- L+288 d: Nominal mission ends.
- Extended mission under consideration.

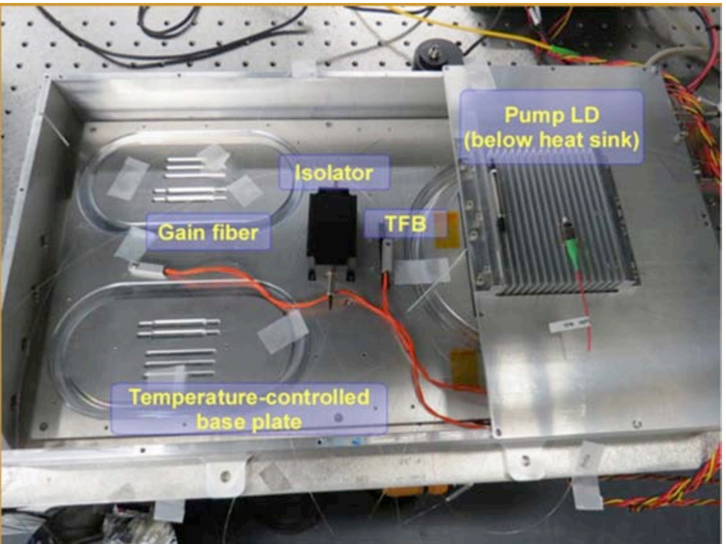
LPF in Kourou Processing Facility

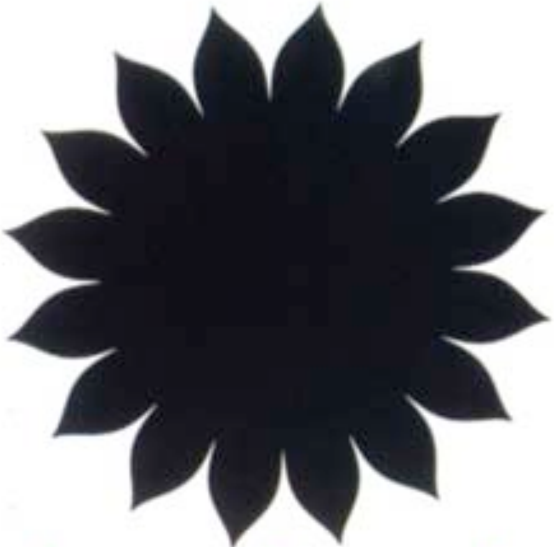


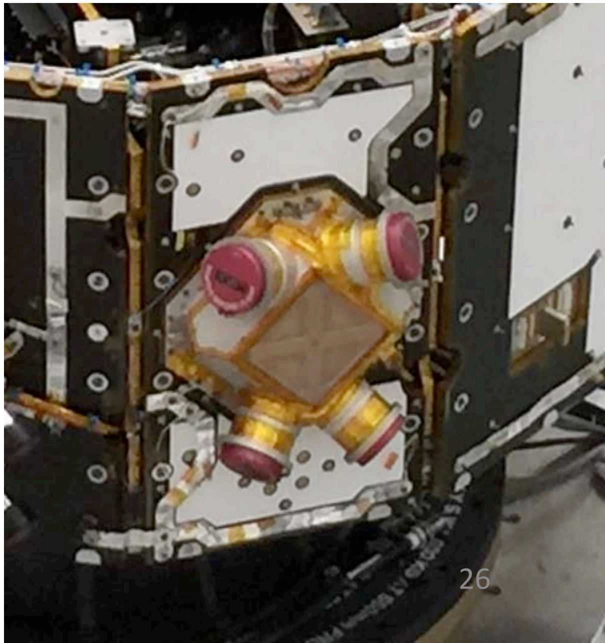




TECHNOLOGY DEVELOPMENT







Technology Development

- Telescope Subsystem – Jeff Livas (GSFC)
  - Demonstrate pathlength stability, stray light and manufacturability
- Phase Measurement System – Bill Klipstein (JPL)
  - Key measurement functions demonstrated
  - Incorporate full flight functionality
- Laser Subsystem – Jordan Camp (GSFC)
  - 1064 nm ECL master oscillator
  - Phase noise of fiber power amplifier
  - Demonstrate end-to-end performance in integrated system
  - Lifetime
- Micronewton Thrusters – John Ziemer (JPL)
  - Propellant storage and distribution for long duration
  - Improve system robustness
  - Improve manufacturing yield
  - Lifetime

Technology Development

- Arm-locking Demonstration – Kirk McKenzie (JPL)
  - Studying a demonstration of laser frequency stabilization with GRACE Follow-On
- Torsion Pendulum – John Conklin (UF)
  - Develop U.S. capability with GRS and torsion pendulum test bed
- Multi-axis Heterodyne Interferometry – Ira Thorpe (GSFC)
  - Investigate test mass/optical bench interface
- UV LEDs – John Conklin (UF)
  - Flight qualify UV LEDs to replace mercury lamps in discharging system
- Optical Bench – Guido Mueller (UF)
  - Investigate alternate designs and fabrication processes to ease manufacturability

LISA researchers at JPL are leading the Laser Ranging Interferometer instrument on the GRACE Follow-On mission.

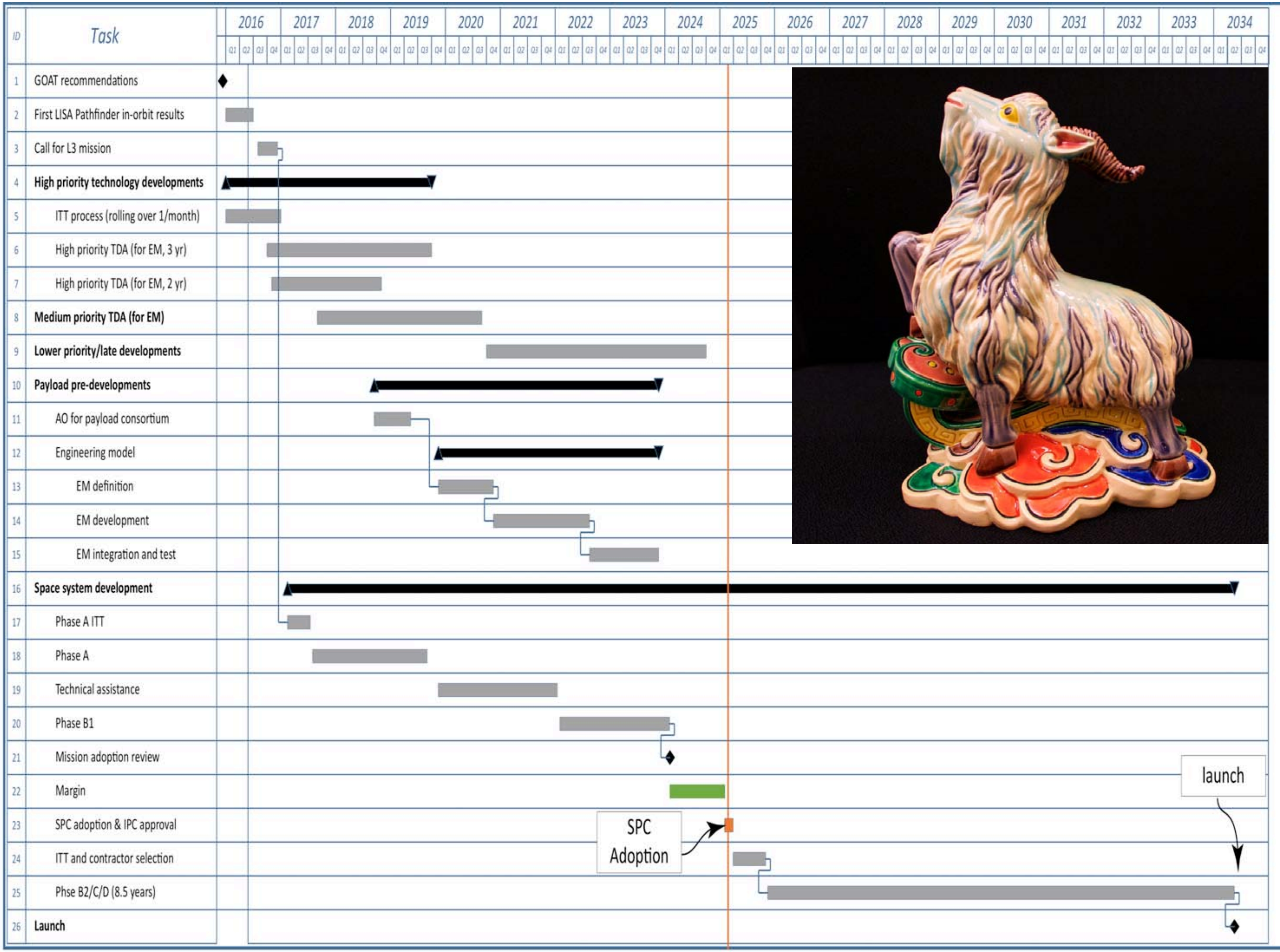
ESA'S COSMIC VISION PROGRAMME 2015-2025

Cosmic Visions 2015-2025

- Next “planning horizon” for ESA science
- NASA withdrew from initial L1 competition in 2011.
- Next Gravitational Observatory (NGO) concept proposed to second L1 competition in 2012.
    - Descoped LISA-like mission to meet ESA cost cap without US participation
    - *Two arms, 1 million Km baselines, 2 year science operations,* 2 launches, mother-daughter configuration.
    - JUICE selected
- “Gravitational Universe” proposed for L2/L3 Competition in 2013
    - NGO the “notional” mission concept.
    - Senior Selection Committee selected Athena for L2 and the Gravitational Universe as the “science theme” for L3, because LPF had not flown.

ESA’s L3 Mission

- Only ‘science theme’ selected, not a mission concept
- Planned launch date is 2034.
- Cost cap is 1B€ to ESA.
- Member states typically contribute an additional 30-35%.
- International partners limited to 20% of total European contribution (about $300M).
- The Astrophysics Strategic Plan calls for NASA to participate as a partner in L3.
- NASA is currently negotiating for a $100-150M contribution. Significantly more would be spent within the US.
- ESA included three U.S. members and one NASA observer on the Gravitational Observatory Advisory Team (GOAT)



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1 GOAT recommendations
2 First LISA Pathfinder in-orbit results
3 Call for L3 mission
4 High priority technology developments
5 ITT process (rolling over 1/month)
6 High priority TDA (for EM, 3 yr)
7 High priority TDA (for EM, 2 yr)
8 Medium priority TDA (for EM)
9 Lower priority/late developments
10 Payload pre-developments
11 AO for payload consortium
12 Engineering model
13 EM definition
14 EM development
15 EM integration and test
16 Space system development
17 Phase A ITT
18 Phase A
19 Technical assistance
20 Phase B1
21 Mission adoption review
22 Margin
23 SPC adoption & IPC approval
24 ITT and contractor selection
25 Phse B2/C/D (8.5 years)
26 Launch
SPC Adoption
launch

NEAR TERM

NASA activities in the near term

- Operations and data analysis on Pathfinder and ST7
- GW Science Interest Group/Physics of the Cosmos Program Analysis Group (POCs: John Conklin and Neil Cornish)
- Continued participation in ESA's GOAT
- Participation in early ESA lead-in activities: mission concept proposal/selection, Phase A start in 2017, …
- Technology development to meet the L3 schedule (ISO TRL6 by Q4 2019)
- NRC Midterm review: in progress, first meeting in October, workshop in December, final meeting in January
- Pre-decadal study in 2017-2018
- Preparations for next decadal (Astro2020)

Summary

- A space-based GW observatory will produce spectacular science.
- The LISA mission concept
  - Long history
  - Very well-studied, including de-scopes
- NASA's Astrophysics Strategic Plan calls for a minority role in ESA's L3 mission opportunity.
- To that end, NASA is
  - Participating in LPF and ST7
  - Developing appropriate technology for a LISA-like mission
  - Preparing to seek an endorsement for L3 participation from the 2020 decadal review